Wearable Tactile Display of Directions for Pedestrian Navigation: comparative Lab and Field Evaluations

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ABSTRACT

We aim to contribute to the development of tactile-based pedestrian navigation systems that help users to navigate urban environments with minimal attention to the user-device interface. This paper describes the design and evaluation of a prototype and reports findings from (i) a lab-based study that directly compared features of two widely researched forms of tactile display: a waist belt and a back array; and (ii) a field evaluation which compared our prototype tactile-based navigation system (TactNav) with a visual mobile maps application (Nokia Maps™). Lab results indicated that the waist belt afforded significantly better performance than the back array across a wide range of metrics. Field results indicated that users' performance with the tactile-based system was equivalent to that with the visual-based system in terms of accuracy while route completion time was significantly faster with the tactile-based directional display.

KEYWORDS: Tactile navigation, pedestrian, wearable.

INDEX TERMS: H.5.2. [Information Interfaces and Presentation]: User Interfaces—Haptic I/O.

1 INTRODUCTION

Recent years have seen enormous growth in the use of pedestrian navigation systems on mobile devices. These systems may deploy different sensory channels (i.e. visual, auditory or tactile) to deliver information, however, tactile interface based navigation systems remain largely at the research and development stages (e.g. [Duistermaat] [Heuten]) while visual and audio based systems are more mature and widely commercialised.

Despite the popularity of visual and audio based portable navigation devices, research has suggested that their use can impede an individual's survey knowledge and disengage users from the environment because they have to concentrate on route instructions [Aslan]. Furthermore, using visual-based systems is reported to require high levels of cognitive effort and mental orientation [Yao] [Huang]. It can be difficult using a map displayed on a small screen in natural light, an auditory display may conflict with other sounds in the environment, and wearing headphones may prevent users from hearing ambient noise crucial to their safety during navigation [Tsukada].

Tactile interaction can help overcome such issues with navigation in situations where visibility and audibility are limited (e.g. [VanErp2005b] [Tan2000]) or unavailable (e.g. [Ross]), in more challenging environments such as a smoke-filled building [Tan2000], and in high workload situations such as search and rescue [Elliott]. Nevertheless, research in the tactile navigation domain is still at a relatively early stage. Major challenges in building practical wearable tactile systems include (i) the design of effective displays, and (ii) the evaluation of potential tactile interfaces in realistic settings.

In tackling the first challenge, we directly compared the two most widely researched interface layouts for tactile directional displays, namely, a back array and a waist belt. In addition, we tested two sizes of the back array to investigate the effects of array size, and conducted a detailed analysis of user performance and preferences. The evaluation study reported in this paper complements our previous work [Srikulwong2010] by taking an egocentric perspective on direction based on the Choremes wayfinding theory [Klippel]. This contrasts with the allocentric perspective used in [Srikulwong2010]). Furthermore, compared to the drawing task used for evaluation in [Srikulwong2010], the directional pointing task used in this study is closer to actual navigation practice because it requires similar skills to those needed when maintaining spatial orientation while navigating in real world environments, i.e. the ability to maintain one's "sense of direction" in order to hold a heading toward the desired destination [Ross].

Collectively, the results from the series of lab studies reported previously [Srikulwong2010] and the studies reported in this paper confirm that the tactile belt is an effective navigation display, at least in controlled experimental conditions. To tackle the second challenge, then, we implemented a tactile pedestrian navigation system called TactNav and carried out a field trial that compared our system's performance with that of a visual mobile maps application in an urban navigation task. We present findings on a range of quantitative and qualitative measures and discuss advantages and disadvantages of each system.

In the following sections, we report both lab- and field-based empirical studies, discuss the findings, and identify key features for the further development of wearable tactile displays.

2 LAB-BASED COMPARISON OF BACK ARRAY AND WAIST BELT TACTILE WEARABLE INTERFACES

We investigated the two most popular forms of wearable tactile display, both of which use the torso as a display site: a back array and a waist belt. These systems provide continuous vibration feedback as a tactile compass as opposed to providing tactile feedback on request (see [Raisamo]). For an overview of various designs and body locations for tactile wearable interfaces, see [Srikulwong2010].

Most of the wearable tactile interfaces worn on the back torso are in the form of a vest that stimulates the user's back with embedded actuators. The interface has a number of actuators arranged in an *m*-by-*n* matrix, e.g. 3x3 (Figure 1A). It generates an illusion of tactile apparent movement also known as phi or beta movement [Lederman] by triggering vibration on adjacent actuators; e.g. the pattern *8-5-2* means go *straight ahead*. The systems have been tested and reported intuitively to present

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spatial information for a drawing task [Tan2003], successfully help sighted users navigate through unfamiliar spaces [Ertan], and effectively assist visually impaired pedestrians in street crossing tasks [Ross].

Waist belt tactile interfaces have a number of embedded actuators distributed around the waist (Figure 1B). A direction is represented by triggering vibration of a single actuator at the corresponding location on the waist; e.g. vibration of *3* means go *straight ahead*. Evaluation results for waist belt interfaces have suggested that they are practical for conveying directional information in operational environments including pedestrian navigation during daytime [Pielot] [Tsukada], in low visibility environments such as at night in densely forested terrain [Duistermaat], navigation in visually cluttered environments such as an aircraft cockpit [VanErp2005b], and in vibrating environments such as in a fast boat [VanErp2005b].

Although both of these forms of wearable tactile displays have been widely studied and found to be effective in experimental trials, our previous work [Srikulwong2010] was the only published evidence that directly compared their performance. That research used a drawing task based on an allocentric concept of direction, however, allocentric direction (e.g. North, South) has been found to be less effective for navigation tasks than egocentric direction (e.g. left, right) [Seager]. These findings suggest that people generally do not conceptualise route directions as cardinal directions. Rather, they code directions relative to their body axis because, during navigation, they have to maintain their orientation as they move. This orientation involves maintaining a concept of one's location and the turning directions with reference both to one's body and to particular features, concrete or abstract, in the environment [Montello].

2.1 Apparatus

For waist belt tactile interfaces, the number of actuators used has varied between six [Heuten] [Pielot], eight [Duistermaat] [Elliott] [Tsukada] [VanErp2005b], 12 [VanErp2001], and 15 [VanErp2005a] actuators. In line with [Duistermaat] [Elliott] [Tsukada] [VanErp2005b], our waist belt interface consisted of eight actuators because each point directly represents one and only one of the potential turning directions in the Choremes model [Klippel]. Actuators had an unequal interspacing (from 50 mm to 130 mm) to account for participants' varying body shape and size.

For the back array, we chose a 3x3 layout of actuators since the majority of previous studies used the 3x3 layout, e.g. [Ross] [Tan2003] [Tan1997] [Young]. For a 4x4 layout, see Ertan et al. [Ertan]. Nevertheless, there is no established optimum value for inter-vibrator distance. Researchers [Tan2003] have tested different values and reported that small participants performed better with an array with an inter-motor distance of 50 mm while bigger participants performed better with a bigger array (inter-motor distance of 80 mm). As a result, we built and evaluated both sizes of the back array. The 50 mm back array consisted of nine actuators mounted into a fabric pad in a 3-by-3 array. The motors had an equal inter-spacing of 50 mm. The 80 mm back array was similar in configuration but had an inter-spacing distance between actuators of 80 mm.

All three interface layouts were connected with the main controller unit which was built using two Phidgets 0/16/16 interface kit controllers (www.phidgets.com) and Solarbotics VPM2 disk motors (www.solarbotics.com) that are 11mm in diameter and 3mm thick. Interfaces were worn over light clothing, i.e. a T-shirt.

For the design of the tactile stimuli, we strictly followed the patterns used in previous research [Tan2003] for all three of the signals' temporal variables (i.e. 12 repetitions of signals at 50-millisecond pulse and inter-pulse duration, giving a 1.2 second stimulus), mapped to Choremes' directions. Two sets of tactile stimuli were used: stimuli set A (Table 1 Column 2) for the 50 mm and the 80 mm back arrays, and set B (Table 1 Column 3) for the belt. The number of pulses and duration of signal were the same across both stimuli sets. Both sets of stimuli had the same constant frequency of 200 Hz.

There were 16 participants, 12 males and 4 females, with an average age of 25. Mean waist size was 86.94 cm (SD 10.9). All participants understood the concept of "direction" and reported no irregularity with tactile perception on their back and around their waist at the time of the experiment. They had never previously worn or experienced tactile displays.

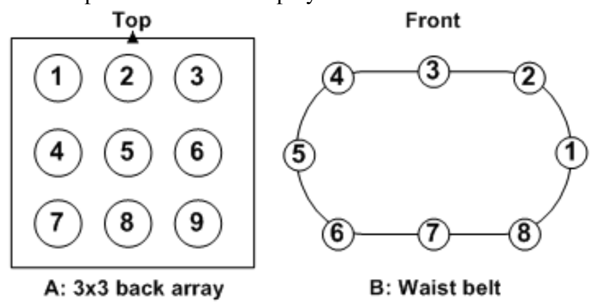

Figure 1. Example layouts of the two interfaces. A: a 3x3 array of vibrating points; B: a waist belt embedded with 8 actuators.

Table 1. Stimuli signal patterns (Note: number in signal patterns set A represents actuator number in Figure 1A; number in signal patterns represents actuator number in Figure 1B).

Direction	Set A: Signal patterns for back arrays	Set B: Signal patterns for the belt
Right	444455556666	111111111111
Left	666655554444	222222222222
Back	222255558888	333333333333
Straight	888855552222	444444444444
Sharp right	111155559999	555555555555
Sharp left	333355557777	666666666666
Half right	777755553333	777777777777
Half left	999955551111	888888888888

2.2 Experimental Procedure

We aimed to investigate whether performance with the three tactile interfaces, namely the 50mm and 80mm arrays and the waist belt, would differ for identifying egocentric directions, in particular those suggested by the Choremes wayfinding theory [Klippel]. We used an egocentric directional pointing task in which participants indicated perceived directions by touching corresponding sensors on surrounding walls. We compared a range of performance measures: response time, correctly perceived directions (accuracy), failure to identify any direction for a given stimulus (breakdowns), and incorrectly identified directions (errors).

All the prototypes were fitted carefully to make sure that all the motors were located at the appropriate body sites to denote the eight directions correctly for each participant, taking into account body size and shape. Prior to the experimental session, participants were given a demonstration of how they would receive the tactile stimuli via each prototype.

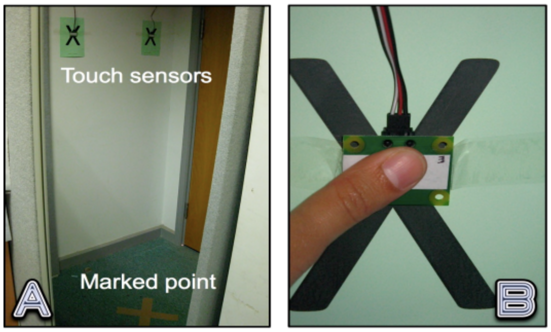

Figure 2. A: A side view of the experimental room, with a marked point at the center of the room. There were eight touch sensors denoting eight directions. B: Touching the sensor.

During the trials, participants stood at a marked point facing *straight ahead* in the middle of a closed 2.25 m^2 room (Figure 2A) that had eight touch sensors on the walls denoting the eight directions. When a tactile stimulus was generated, the participant responded to the direction she perceived by tapping on the corresponding touch sensor on the wall (Figure 2B). Each participant responded to eight stimuli for each interface. We deliberately did not repeat the signals for each interface because we wanted to learn about users' initial reactions to and preferences between two forms of technology that were new to them. We are interested in the immediate usability of the interfaces because a key factor in successfully introducing new personal technologies lies in their off the shelf usability. The order of conditions was counterbalanced. Response direction and response time (in ms) were automatically logged.

2.3 Results

Mean performance measures are given in Table 2. A one-way repeated-measures ANOVA with Interface as the independent variable was used to analyze the results.

Table 2. Mean accuracy, breakdowns, errors and response time across three tactile interfaces, scores: n of 8, time: in seconds. SDs in parentheses.

Measures	50mm Array	80mm Array	Waist Belt
Accuracy	4.50 (0.82)	5.44 (1.21)	7.62 (0.50)
Errors	2.81 (1.17)	2.38 (1.26)	0.38 (0.50)
Breakdowns	0.69 (0.87)	0.19 (0.54)	0.00 (0.00)
Time	4.12 (1.24)	2.61 (0.67)	1.86 (0.68)

For the accuracy scores (Table 2, first row), Mauchly's test indicated that the assumption of sphericity had been violated ($X^2(2) = 7.71$, $p<0.05$); therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon=0.70$). The results showed a significant effect by tactile interface on accuracy ($f_{1.41,21.08} = 90.05$, $p<0.002$). Post hoc Bonferroni pairwise tests revealed significant main effects between the 50mm array and the belt ($p<0.002$), between the 80mm array and the belt ($p<0.002$), and between the 50mm and 80mm arrays ($p=0.002$). The results suggest that participants performed best using the belt and worst using the 50mm array.

Participants made most errors (Table 2, second row) with the 50mm array and fewest with the belt. A one-way repeated-measures ANOVA found a significant effect by tactile interface on errors ($f_{2,30} = 43.52$, $p<0.002$). Post hoc Bonferroni tests showed significant effects between the 50mm array and the belt ($p<0.002$), and between the 80mm array and the belt ($p<0.002$). There was no significant difference between the 50mm and 80mm arrays ($p=0.39$, n.s.). With the arrays, participants performed worst in accuracy and response time with vertical signals (*straight* and *back*). This may be due to an effect of the midline gap along the spine on participants' backs [Tan2003]. With the belt, participants performed equally well in all directions.

For breakdowns, i.e. failure to identify a direction at all (Table 2, third row), a one-way repeated measures ANOVA found a significant effect by tactile interface on breakdowns ($f_{2,30} = 6.53$, $p<0.05$). Post hoc Bonferroni pairwise tests showed a significant main effect between the 50mm array and the belt ($p<0.05$). There was no significant difference between the 80mm array and the belt ($p=0.56$, n.s.) or between the 50mm and 80mm arrays ($p=0.12$, n.s.).

Mean response times are shown in the fourth row of Table 2. Mauchly's test indicated that the assumption of sphericity had been violated ($X^2(2) = 10.77$, $p<0.05$); therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = 0.65$). A one-way repeated measures ANOVA found a significant effect by tactile interface on response time ($f_{1.30,\ 19.52} = 31.80$, $p<0.002$). Post hoc Bonferroni pairwise tests showed significant effects between the 50mm array and the belt ($p<0.002$), between the 80mm array and the belt ($p<0.002$) and between the 50mm and 80mm arrays ($p=0.001$). The results suggest that participants responded fastest using the belt and slowest using the 50mm array.

Between the two back arrays, 81% of participants preferred the 80mm array and it was regarded as the more effective size of array configuration for most users. All participants preferred the waist belt to both back arrays because it was easy to use and smaller in size. Additionally, the waist belt gave them confidence in identifying directions because the signals were precise and required little effort to memorise and interpret.

2.4 Discussion

With the belt interface, there was evidence of systematic error of 45 degrees between the stimulated and the perceived directions. This phenomenon may be explained by Van Erp's [VanErp2005] findings that a bias was usually found to be towards the midsagittal plane, that is, directions were perceived as more towards the navel or spine than they actually were. Van Erp suggested that to reduce such error, a torso-related transfer function (TRTF) that maps direction to a unique location on the torso could be adopted [VanErp2005]. With both array interfaces, the angle of directional identification error was random across conditions.

Another limitation with the lab experiments may be in not isolating the three factors (stimuli patterns, body contact areas and actuator layouts) that may contribute to the belt's achieving better performance. As we wanted directly to compare the devices' layout and signal generation on their effectiveness, we had to fully replicate the original designs. Future research could investigate the effects of alternative instantiations of each of these factors.

2.5 Conclusion of the Laboratory Study

Overall, the results strongly suggest that a waist belt with absolute point vibration is a better choice for an effective wearable tactile display than a back array with the illusion of tactile apparent movement, at least for the task studied. Hence, we accepted the experimental hypothesis.

The findings suggest that performance with the two layouts differs with respect to supporting the user in identifying egocentric directions. This may be explained because the belt imposes very little cognitive load on the user in matching between the different frames of reference (i.e. the device, the self and the world), since all three frames effectively align. In contrast, the back array displays require the users to interpret and transform the signals perceived via the device on their back and match them to the self's egocentric perspective and to the surrounding environment.

The back array may be useful in some circumstances, such as where a tactile display cannot be worn or when it is more appropriate to embed an array into everyday objects such as chairs or car seats. In these cases it may be worth conducting further research to improve the effectiveness of the back array.

To further explore the ecological validity of these lab-based results on the performance of tactile-based navigation systems in the field, we next compared the performance of our prototype tactile navigation system in its most effective form, i.e. the waist belt, to that of a visual navigation system on a mobile phone.

3 Field-based evaluation of TactNav and a visual mobile navigation system

Results from the lab studies gave us some confidence that participants should be able to navigate effectively using the tactile belt. Extending the tactile belt prototype with an integrated GPS system, we developed a prototype tactile pedestrian navigation system that we called TactNav. Our goal was to evaluate TactNav's performance in comparison to that of a visual mobile map-based system, in this case Nokia Maps.

In order to make the systems more directly comparable, we altered and limited a number of spatial information types on the visual mobile maps and added new types of tactile spatial information to TactNav. We hypothesised that the different navigation aids would have an effect on performance. Specifically, navigation with the tactile-based system would be faster than with the visual-based system. We recorded several measures of performance including route completion time and accuracy, i.e. correctly identified directions.

3.1 Apparatus

To enable TactNav for use in the field, we added a GPS unit (QStarz's BT-Q1000) to the waist belt prototype. The system's design is based on an assumption that the route is navigable by establishing sequences of intermediate waypoints and proceeding forward in the direction of the next destination on the route [Seager]. Once navigation starts, the system receives the user's current position from the GPS unit, constantly compares positioning data with the pre-determined turning points (TP), and generates a set of two tactile signals on any corresponding actuator when users enter a TP's "hot zone" (radius of 10 meters from the TP). The first signal is given at the edge of the hot zone and the second signal is given three seconds later.

The apparatus for the visual mobile maps condition was a Nokia N95 handset running Nokia Maps 2.0 [Nokia]. To eliminate a usability issue with the orientation of maps, our participants always navigated using the "heading-up" maps mode that has been reported [Seager] to require less mental effort than "north-up" maps[1]. During our field trial, we turned off the angular view and voice guidance functions. Information types other than direction were disabled so that the information provided by the visual maps system was closely equivalent to that provided by the tactile system.

For TactNav, the system provided directional information that served as waypoint instructions (Stimuli set B was used – see Table 1). To compensate for TactNav's lack of ability to display point localisation signals, a *straight* signal was used as a confirmation cue, generated at pre-determined points on long segments of routes. These cues were intended to give users confidence that they were traveling in the right direction, comparable to when pedestrians use visual structural landmarks to confirm a correct navigation decision. Additionally, TactNav provided a notification when the intended destination was reached by vibrating all the actuators simultaneously.

For Nokia Maps, two types of pin symbols were used to represent (1) confirmation cues and (2) destination reached. Confirmation cues appeared as blue pins on the maps at the same points as the confirmation vibrations in TactNav. A visual notification of a white star with a blue flag designated destination reached (Figure 3).

There were 24 paid participants, 11 males and 13 females with an average age of 29. Half of the participants navigated with the mobile maps and the other half used TactNav to navigate the same route. For the TactNav condition, none of the 12 participants had ever used a tactile-based navigation system. The smallest participant had a 61 cm waist size and the largest 96 cm (mean 79.17, SD 9.89). For the visual-based navigation, 83% of participants had never used a mobile maps application and 92% were not familiar with the particular mobile handset used.

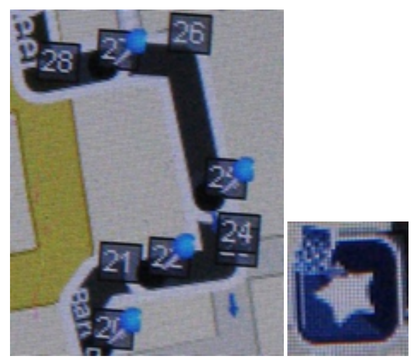

Figure 3. Confirmation cues and destination point in the visual mobile map application; Left – confirmation points, and Right – a symbol for destination reached.

3.2 Experimental Procedure

Participants navigated on foot in an urban setting in the city of Bath, UK, where there is a relatively large number of objects and cues in the space, to reach an unfamiliar destination. Sessions took place over 10 days.

A pre-determined 1.3 km route containing 20 TPs (including the start and end points) was set up. Each system constantly compared participants' current location (by GPS) with the pre-determined route and triggered an appropriate directional cue (visual or tactile according to the different technologies deployed) at each turning point. No other concurrent activity was performed or allowed during the experiment.

In each condition, as they walked the route shadowed by the experimenter, participants responded to any perceived directional cue by speaking out loud their turn-taking decision according to the direction perceived. Their route and journey duration were automatically logged by the systems.

[1] Heading-up maps align the top of the map display to the user's current orientation while north-up maps always show north at the top of the map display.

3.3 Results

3.3.1 Performance

We compared a range of performance measures: completion time, walking pace, correct and wrong turns, and missed signals. Correct turns refer to the number of correctly identified directions. Wrong turns indicate the number of incorrectly identified directions. Missed signals reflect the number of times participants failed to notice the stimulus. Any idle time caused by participants pausing to wait for GPS signals was subtracted from the overall recorded completion time. Results are shown in Table 3.

Results indicated that users' performance with the tactile-based navigation system was equivalent to that of the visual-based system in terms of accuracy while route completion time was significantly faster with the tactile-based navigation system.

With the tactile system, a number of missed signals were reported, i.e. the user did not perceive the tactile stimulus. Independent samples t-tests showed no significant effect of the two systems on correct turns (t_{22} = -1.23, n.s.) or on wrong turns (t_{22} = -0.46, n.s.).

Table 3. Mean scores of completion time and walking pace (Time: mins, Pace: km/h, Turns: n of 20). SDs in parentheses.

	TactNav			Visual Mobile Maps		
	Mean	**Min**	**Max**	**Mean**	**Min**	**Max**
Missed signals	0.67 (0.99)	0	3	n/a	n/a	n/a
Correct turns	18.58 (1.17)	17	20	19.08 (0.79)	17	20
Wrong turns	0.75 (0.97)	0	3	0.92 (0.79)	0	3
Completion time	20.4 (1.8)	16.2	22.8	23.2 (0.05)	20.0	30.0
Walking pace	3.9 (0.39)	3.45	4.81	3.39 (0.38)	2.60	3.94

With the visual mobile maps system, the users completed the route in a mean of 23 minutes. With the TactNav system, the users completed the route faster, with a mean of 20 minutes. The average walking pace of the TactNav users (3.9 km/h) was almost equal to the normal speed of adult pedestrians at 4.2 - 4.4 km/h [Knoblauch]. Independent samples t-tests found a significant effect of systems on route completion time (t_{22} = -3.18, $p < 0.01$) and walking pace (t_{22} = 3.26, $p < 0.01$). In other words, participants using TactNav moved more quickly than the Nokia Maps' users. Hence, we accepted the hypothesis.

3.3.2 Other Qualitative Results

Our participants thought that either system could conveniently be used to complement paper-based maps (t_{22} = 0.35, n.s.) but preferred the TactNav system. An important additional aspect that should be noted here is that the wearability and aesthetics of tactile systems will be crucial to user acceptance. With a computer in a backpack and a number of visible wires, our current TactNav prototype requires some improvements in that respect.

3.4 Discussion

3.4.1 The Effect of GPS Availability on Visual Maps Orientation and the Temporary Absence of Tactile Cues

Ease of navigation and task performance with mobile maps are influenced by map alignment to the orientation of the user [Smets]. The mobile maps application used in our study starts with a north-up map and when the user starts walking it switches to a heading-up map. The device infers user orientation from the recorded direction of travel up to that point. This initial switch took up to 30 seconds and subsequent map rotations suffered from delays. This was due to a combination of unavailable satellite signals and the implementation logic of the application, which requires several recorded GPS fixes in order to resolve the heading direction. Therefore, in order to maintain heading-up maps, users often physically rotated the device to match the orientation of the map with the direction of travel. They found it quite difficult to work out the correct orientation but would eventually manage to continue with the journey.

TactNav's users also suffered from the same GPS availability problem. However, without a screen to look at, users reported becoming frustrated and feeling lost; some remained idle at the spot while some walked around in an attempt to acquire a GPS signal. Once the GPS signal came through and the system was able to deliver a corresponding tactile cue, they reported that the route navigation could be continued with minimum effort.
Thus, both systems suffered from the same GPS availability problem in "urban canyons", leading to delays with each system. Nevertheless, the main factor affecting users' completion time with the visual mobile maps was the requirement to transfer amongst the different frames of reference: the world, the device (in this case, the map) and the user.

3.4.2 Attention

In the tactile condition, participants reported a number of occasions when they did not perceive a signal although the system had generated it. We report these incidents as missed signals in Table 3. They may be due to a lack of attention to the navigation system, either because the participant became habituated to wearing it and no longer noticed it or because of competing demands for their attention in a busy urban environment. Participants in the tactile condition navigated with their eyes free from looking at the system and were found to look constantly at the surroundings. The vibration strength, which seemed to be perfectly adequate in the lab, turned out to be rather too weak in the field. We could address optimizing the level of tactile attention by increasing the size of the actuators as well as increasing signal strength or by giving users control of the signal strength.

On the other hand, the visual maps users were observed looking intently at the phone screen and frequently manipulating the phone with one or both hands. The high demand on visual attention led to a number of minor incidents during the course of the experiment, e.g. participants tripping over objects or uneven pavements.

3.4.3 Confidence in Navigation

According to qualitative results, GPS precision and response time contributed to participants' confidence levels in both the visual and tactile systems. For the visual mobile maps, participants were impressed by the application's response time but were disappointed with the GPS precision. With the tactile navigation, participants were excited by the unfamiliar technology. Nevertheless, unfamiliarity as well as slow response times, due to poor GPS reception decreased their confidence level.

3.5 Limitations of the Field Study

There is no concrete measurement of variability in our respondents' spatial abilities that might contribute to the results. Another major limitation of this evaluation is having participants walking in their residential town which could possibly bias results on navigation performance. To compensate any potential preconception, we designed unusual and slightly complex yet realistic paths for the experiments. Additionally, routes were unknown to participants. Nevertheless, we insist that TactNav should be evaluated in unfamiliar areas and in different urban settings to confirm its usability and effectiveness. This is considered as our future research direction.

3.6 Conclusion of the Field Evaluation

We compared the performance of our TactNav system with an example of a visual mobile maps system. Results showed that performance accuracy with tactile-based navigation was comparable to that with visual-based navigation, while TactNav significantly outperformed the mobile maps application in route completion time. Hence, we accepted the hypothesis.

Observations from our field evaluation allow us to identify advantages and disadvantages of each system. For the visual-based navigation system, advantages include the ability to provide (i) overview information of the space navigated and (ii) complex and semantically rich information such as categories of landmarks and street names. Nonetheless, this semantically rich information may present challenges since users may require considerable time and effort to cross-reference the corresponding features of the environment with the map. Disadvantages with the visual maps system also include the delay switching between north-up and heading-up map modes, prompting users frequently to adjust a phone's physical orientation to maintain a heading-up map orientation on the display, leading to user confusion and longer route completion time.

The tactile-based system is convenient because users do not have to carry or look at the device. As a result, they can have their hands and eyes free for other tasks. We have demonstrated that users who are not good at reading maps or lack orientation and wayfinding skills can easily and successfully navigate with a tactile interface. In addition, the system works in low visibility and noisy environments. During our prototype evaluation, practical issues were raised by users for future system improvement. These issues included aesthetics and lack of features such as an automatic re-routing function, estimated distance to target points and cues for landmarks.

4 SUMMARY

In this paper, we report results from a series of empirical studies that addressed the effectiveness of delivering spatial tactile signals through two interface layouts and investigated the use of a tactile interface compared with a visual map-based interface for assisting pedestrian navigation in urban environments. We found that high navigation performance can be achieved through an effective wearable device that displays unimodal tactile output.

Our empirical studies suggest that tactile displays have the potential to be deployed as an alternative to conventional visual displays. Our prototype tactile display, worn on the body, helps reduce users' cognitive demands by eliminating the need to match between the world, the device and the self frames of reference. It uses an egocentric approach to provide concise and effective directional information to aid pedestrian navigation tasks.

In recent years, navigation between places has been made easier by the availability of satellite navigation systems. Nevertheless, despite their perceived usefulness, their primarily visual displays have imposed some problems on their users. Given the potential of the use of touch as an alternative display modality, further research is required towards the development of a practical, convenient and robust tactile-based navigation system. Our ongoing work includes investigating the use of tactile feedback to convey other types of spatial information such as landmarks [Srikulwong2011a] [Srikulwong2011b]. Future work will focus on the addition of an initialisation interface and re-routing functionality as well as an integrative evaluation of the advanced system in the field.

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